CHAPTER 21 (Odd)

1. a. $M = k\sqrt{L_pL_s} \Rightarrow L_s = \dfrac{M^2}{L_pk^2} = \dfrac{(80 \text{ mH})^2}{(50 \text{ mH})(0.8)^2} = \mathbf{0.2\ H}$

   b. $e_p = N_p\dfrac{d\phi_p}{dt} = (20)(0.08 \text{ Wb/s}) = \mathbf{1.6\ V}$

   $e_s = kN_s\dfrac{d\phi_p}{dt} = (0.8)(80 \text{ t})(0.08 \text{ Wb/s}) = \mathbf{5.12\ V}$

   c. $e_p = L_p\dfrac{di_p}{dt} = (50 \text{ mH})(0.03 \times 10^3 \text{ A/s}) = \mathbf{15\ V}$

   $e_s = M\dfrac{di_p}{dt} = (80 \text{ mH})(0.03 \times 10^3 \text{ A/s}) = \mathbf{24\ V}$

3. a. $L_s = \dfrac{M^2}{L_pk^2} = \dfrac{(80 \text{ mH})^2}{(50 \text{ mH})(0.9)^2} = \mathbf{158.02\ mH}$

   b. $e_p = N_p\dfrac{d\phi_p}{dt} = (300 \text{ t})(0.08 \text{ Wb/s}) = \mathbf{24\ V}$

   $e_s = kN_s\dfrac{d\phi_p}{dt} = (0.9)(25 \text{ t})(0.08 \text{ Wb/s}) = \mathbf{1.8\ V}$

   c. e_p and e_s the same as problem 1: $e_p = \mathbf{15\ V}$, $e_s = \mathbf{24\ V}$

5. a. $E_s = \dfrac{N_s}{N_p}E_p = \dfrac{30 \text{ t}}{240 \text{ t}}(25 \text{ V}) = \mathbf{3.125\ V}$

   b. $\Phi_{m(\max)} = \dfrac{E_p}{4.44\, fN_p} = \dfrac{25 \text{ V}}{(4.44)(60 \text{ Hz})(240 \text{ t})} = \mathbf{391.02\ \mu Wb}$

7. $f = \dfrac{E_p}{(4.44)N_p\Phi_{m(\max)}} = \dfrac{25 \text{ V}}{(4.44)(8 \text{ t})(12.5 \text{ mWb})} = \mathbf{56.31\ Hz}$

9. $Z_p = \dfrac{V_g}{I_p} = \dfrac{1600 \text{ V}}{4 \text{ A}} = \mathbf{400\ \Omega}$

11. $I_L = I_s = \dfrac{V_L}{Z_L} = \dfrac{240 \text{ V}}{20\ \Omega} = 12 \text{ A}$

    $\dfrac{I_s}{I_p} = a = \dfrac{N_p}{N_s} \Rightarrow \dfrac{12 \text{ A}}{0.05 \text{ A}} = \dfrac{N_p}{50}$

    $N_p = \dfrac{50(12)}{0.05} = \mathbf{12{,}000\ turns}$

13. a. $Z_p = a^2 Z_L \Rightarrow a = \sqrt{\dfrac{Z_p}{Z_L}}$

$$Z_p = \frac{V_p}{I_p} = \frac{10\ \text{V}}{20\ \text{V}/72\ \Omega} = 36\ \Omega$$

$$a = \sqrt{\frac{36\ \Omega}{4\ \Omega}} = \mathbf{3}$$

b. $\dfrac{V_s}{V_p} = \dfrac{N_s}{N_p} = \dfrac{1}{3} \Rightarrow V_s = \dfrac{1}{3}V_p = \dfrac{1}{3}(10\ \text{V}) = \mathbf{3\frac{1}{3}\ V}$

$$P = \frac{V_s^2}{Z_s} = \frac{(3.33\ \text{V})^2}{4\ \Omega} = \mathbf{2.78\ W}$$

15. a. $a = \dfrac{N_p}{N_s} = \dfrac{4\text{t}}{1\text{t}} = 4$

$R_e = R_p + a^2 R_s = 4\ \Omega + (4)^2\ 1\ \Omega = 20\ \Omega$

$X_e = X_p + a^2 X_s = 8\ \Omega + (4)^2\ 2\ \Omega = 40\ \Omega$

$\mathbf{Z}_p = \mathbf{Z}_{R_e} + \mathbf{Z}_{X_e} + a^2\mathbf{Z}_{X_L} = 20\ \Omega + j40\ \Omega + j(4)^2\ 20\ \Omega$

$= 20\ \Omega + j40\ \Omega + j320\ \Omega = 20\ \Omega + j360\ \Omega = \mathbf{360.56\ \Omega\ \angle 86.82^\circ}$

b. $\mathbf{I}_p = \dfrac{\mathbf{V}_g}{\mathbf{Z}_p} = \dfrac{120\ \text{V}\ \angle 0^\circ}{360.56\ \Omega\ \angle 86.82^\circ} = \mathbf{332.82\ mA\ \angle -86.82^\circ}$

c. $\mathbf{V}_{R_e} = (I\angle\theta)(R_e\angle 0^\circ) = (332.82\ \text{mA}\ \angle -86.82^\circ)(20\ \Omega\ \angle 0^\circ)$

$= \mathbf{6.656\ V\ \angle -86.82^\circ}$

$\mathbf{V}_{X_e} = (I\angle\theta)(X_e\angle 90^\circ) = (332.82\ \text{mA}\ \angle -86.32^\circ)(40\ \Omega\ \angle 90^\circ)$

$= \mathbf{13.313\ V\ \angle 3.18^\circ}$

$\mathbf{V}_{X_L} = \mathbf{I}(a^2\mathbf{Z}_{X_L}) = (332.82\ \text{mA}\ \angle -86.82^\circ)(320\ \Omega\ \angle 90^\circ)$

$= \mathbf{106.50\ V\ \angle 3.18^\circ}$

17. —

19. $L_{T_{(+)}} = L_1 + L_2 + 2M_{12}$

$M_{12} = k\sqrt{L_1 L_2} = (0.8)\sqrt{(200\ \text{mH})(600\ \text{mH})} = \mathbf{277\ mH}$

$L_{T_{(+)}} = 200\ \text{mH} + 600\ \text{mH} + 2(277\ \text{mH}) = \mathbf{1.354\ H}$

21. $\mathbf{E}_1 - \mathbf{I}_1[\mathbf{Z}_{R_1} + \mathbf{Z}_{L_1}] - \mathbf{I}_2[\mathbf{Z}_m] = 0$

$\mathbf{I}_2[\mathbf{Z}_{L_2} + \mathbf{Z}_{R_L}] + \mathbf{I}_1[\mathbf{Z}_m] = 0$

$\mathbf{I}_1(\mathbf{Z}_{R_1} + \mathbf{Z}_{L_1}) + \mathbf{I}_2(\mathbf{Z}_m) = \mathbf{E}_1$

$\mathbf{I}_1(\mathbf{Z}_m) + \mathbf{I}_2(\mathbf{Z}_{L_2} + \mathbf{Z}_{R_L}) = 0$ $\qquad X_m = -\omega M\ \angle 90^\circ$

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23. a. $a = \dfrac{N_p}{N_s} = \dfrac{V_p}{V_s} = \dfrac{2400\text{ V}}{120\text{ V}} = \mathbf{20}$

b. $10{,}000\text{ VA} = V_s I_s \Rightarrow I_s = \dfrac{10{,}000\text{ VA}}{V_s} = \dfrac{10{,}000\text{ VA}}{120\text{ V}} = \mathbf{83.33\ A}$

c. $I_p = \dfrac{10{,}000\text{ VA}}{V_p} = \dfrac{10{,}000\text{ VA}}{2400\text{ V}} = \mathbf{4.167\ A}$

d. $a = \dfrac{V_p}{V_s} = \dfrac{120\text{ V}}{2400\text{ V}} = 0.05 = \dfrac{1}{20}$

$I_s = \dfrac{10{,}000\text{ VA}}{2400\text{ V}} = \mathbf{4.167\ A},\ I_p = \mathbf{83.33\ A}$

25. a. $\mathbf{E}_s = \dfrac{N_s}{N_p}\mathbf{E}_p$

$= \dfrac{25\text{ t}}{100\text{ t}}(100\text{ V} \angle 0°) = 25\text{ V} \angle 0° = \mathbf{V}_L$

$\mathbf{I}_s = \dfrac{\mathbf{E}_s}{\mathbf{Z}_L} = \dfrac{25\text{ V} \angle 0°}{5\ \Omega \angle 0°} = \mathbf{5\ A \angle\ 0°} = \mathbf{I}_L$

b. $\mathbf{Z}_i = a^2\mathbf{Z}_L = \left[\dfrac{N_p}{N_s}\right]^2 \mathbf{Z}_L = \left[\dfrac{100\text{ t}}{25\text{ t}}\right]^2 5\ \Omega \angle 0° = (4)^2\, 5\ \Omega \angle 0° = \mathbf{80\ \Omega \angle 0°}$

c. $\mathbf{Z}_{1/2} = \dfrac{1}{4}\mathbf{Z}_i = \dfrac{1}{4}(80\ \Omega \angle 0°) = \mathbf{20\ \Omega \angle 0°}$

27. a. $\mathbf{E}_2 = \dfrac{N_2}{N_1}\mathbf{E}_1 = \left[\dfrac{40\text{ t}}{120\text{ t}}\right](120\text{ V} \angle 60°) = \mathbf{40\ V \angle 60°}$

$\mathbf{I}_2 = \dfrac{\mathbf{E}_2}{\mathbf{Z}_2} = \dfrac{40\text{ V} \angle 60°}{12\ \Omega \angle 0°} = \mathbf{3.33\ A \angle 60°}$

$\mathbf{E}_3 = \dfrac{N_3}{N_1}\mathbf{E}_1 = \left[\dfrac{30\text{ t}}{120\text{ t}}\right](120\text{ V} \angle 60°) = \mathbf{30\ V \angle 60°}$

$\mathbf{I}_3 = \dfrac{\mathbf{E}_3}{\mathbf{Z}_3} = \dfrac{30\text{ V} \angle 60°}{10\ \Omega \angle 0°} = \mathbf{3\ A \angle 60°}$

b. $\dfrac{1}{R_1} = \dfrac{1}{(N_1/N_2)^2 R_2} + \dfrac{1}{(N_1/N_3)^2 R_3}$

$= \dfrac{1}{(120\text{ t}/40\text{ t})^2 12\ \Omega} + \dfrac{1}{(120\text{ t}/30\text{ t})^2 10\ \Omega}$

$\dfrac{1}{R_1} = \dfrac{1}{108\ \Omega} + \dfrac{1}{160\ \Omega} = 0.0155\text{ S}$

$R_1 = \dfrac{1}{0.0155\text{ S}} = \mathbf{64.52\ \Omega}$

29. $\mathbf{E}_1 - \mathbf{I}_1\mathbf{Z}_1 - \mathbf{I}_1\mathbf{Z}_{L_1} - \mathbf{I}_2(-\mathbf{Z}_{M_{12}}) - \mathbf{I}_3(+\mathbf{Z}_{M_{13}}) = 0$

or $\mathbf{E}_1 - \mathbf{I}_1[\mathbf{Z}_1 + \mathbf{Z}_{L_1}] + \mathbf{I}_2\mathbf{Z}_{M_{12}} - \mathbf{I}_3\mathbf{Z}_{M_{13}} = 0$

$-\mathbf{I}_2(\mathbf{Z}_2 + \mathbf{Z}_3 + \mathbf{Z}_{L_2}) + \mathbf{I}_3\mathbf{Z}_2 - \mathbf{I}_1(-\mathbf{Z}_{M_{12}}) = 0$

or $-\mathbf{I}_2(\mathbf{Z}_2 + \mathbf{Z}_3 + \mathbf{Z}_{L_2}) + \mathbf{I}_3\mathbf{Z}_2 + \mathbf{I}_1\mathbf{Z}_{M_{12}} = 0$

$-\mathbf{I}_3(\mathbf{Z}_2 + \mathbf{Z}_4 + \mathbf{Z}_{L_3}) + \mathbf{I}_2\mathbf{Z}_2 - \mathbf{I}_1(+\mathbf{Z}_{M_{13}}) = 0$

or $-\mathbf{I}_3(\mathbf{Z}_2 + \mathbf{Z}_4 + \mathbf{Z}_{L_3}) + \mathbf{I}_2\mathbf{Z}_2 - \mathbf{I}_1\mathbf{Z}_{M_{13}} = 0$

$$\therefore \quad \begin{aligned}
&[\mathbf{Z}_1 + \mathbf{Z}_{L_1}]\mathbf{I}_1 - \mathbf{Z}_{M_{12}}\mathbf{I}_2 + \mathbf{Z}_{M_{13}}\mathbf{I}_3 = \mathbf{E}_1\\
&\mathbf{Z}_{M_{12}}\mathbf{I}_1 - [\mathbf{Z}_2 + \mathbf{Z}_3 + \mathbf{Z}_{L_2}]\mathbf{I}_2 + \mathbf{Z}_2\mathbf{I}_3 = 0\\
&\mathbf{Z}_{M_{13}}\mathbf{I}_1 \qquad \mathbf{Z}_2\mathbf{I}_2 + [\mathbf{Z}_2 + \mathbf{Z}_4 + \mathbf{Z}_{L_3}]\mathbf{I}_3 = 0
\end{aligned}$$

CHAPTER 21 (Even)

2. a. $k = 1$

(a) $L_s = \dfrac{M^2}{L_p k^2} = \dfrac{(80 \text{ mH})^2}{(50 \text{ mH})(1)^2} = \mathbf{128\ mH}$

(b) $e_p = \mathbf{1.6\ V}$, $e_s = kN_s \dfrac{d\phi_p}{dt} = (1)(80 \text{ t})(0.08 \text{ Wb}/s) = \mathbf{6.4\ V}$

(c) $e_p = \mathbf{15\ V}$, $e_s = \mathbf{24\ V}$

b. $k = 0.2$

(a) $L_s = \dfrac{M^2}{L_p k^2} = \dfrac{(80 \text{ mH})^2}{(50 \text{ mH})(0.2)^2} = \mathbf{3.2\ H}$

(b) $e_p = \mathbf{1.6\ V}$, $e_s = kN_s \dfrac{d\phi_p}{dt} = (0.2)(80 \text{ t})(0.08 \text{ Wb/s}) = \mathbf{1.28\ V}$

(c) $e_p = \mathbf{15\ V}$, $e_s = \mathbf{24\ V}$

4. a. $E_s = \dfrac{N_s}{N_p} E_p = \dfrac{64 \text{ t}}{8 \text{ t}}(25 \text{ V}) = \mathbf{200\ V}$

b. $\Phi_{\text{max}} = \dfrac{E_p}{4.4 f N_p} = \dfrac{25 \text{ V}}{4.44(60 \text{ Hz})(8 \text{ t})} = \mathbf{11.73\ mWb}$

6. $E_p = \dfrac{N_p}{N_s} E_s = \dfrac{60 \text{ t}}{720 \text{ t}}(240 \text{ V}) = \mathbf{20\ V}$

8. a. $I_L = aI_p = \left[\dfrac{1}{5}\right](2 \text{ A}) = \mathbf{0.4\ A}$

$V_L = I_L Z_L = \left[\dfrac{2}{5} \text{ A}\right](2\ \Omega) = \mathbf{0.8\ V}$

b. $Z_{\text{in}} = a^2 Z_L = \left[\dfrac{1}{5}\right]^2 2\ \Omega = \mathbf{0.08\ \Omega}$

10. $V_g = aV_L = \left[\dfrac{1}{4}\right](1200 \text{ V}) = \mathbf{300\ V}$

$I_p = \dfrac{V_g}{Z_i} = \dfrac{300 \text{ V}}{4\ \Omega} = \mathbf{75\ A}$

12. a. $a = \dfrac{N_p}{N_s} = \dfrac{400 \text{ t}}{1200 \text{ t}} = \dfrac{1}{3}$

$Z_i = a^2 Z_L = \left[\dfrac{1}{3}\right]^2 [9\ \Omega + j12\ \Omega] = 1\ \Omega + j1.333\ \Omega = 1.667\ \Omega\ \angle 53.13°$

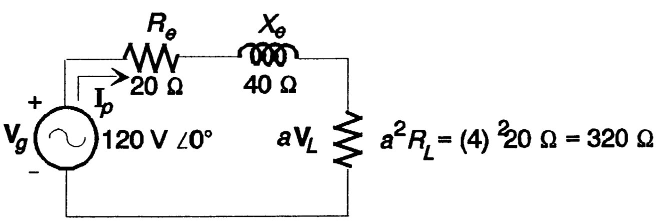
$I_p = V_g/Z_i = 100 \text{ V}/1.667\ \Omega = \mathbf{60\ A}$

b. $I_L = aI_p = \frac{1}{3}(60\text{ A}) = \mathbf{20\text{ A}},\ V_L = I_L Z_L = (20\text{ A})(15\ \Omega) = \mathbf{300\text{ V}}$

14. a. $R_e = R_p + a^2 R_s = 4\ \Omega + (4)^2\ 1\ \Omega = \mathbf{20\ \Omega}$

b. $X_e = X_p + a^2 X_s = 8\ \Omega + (4)^2\ 2\ \Omega = \mathbf{40\ \Omega}$

c.



d. $\mathbf{I}_p = \dfrac{\mathbf{V}_g}{\mathbf{Z}_p} = \dfrac{120\text{ V}\ \angle 0°}{20\ \Omega + 320\ \Omega + j40\ \Omega} = \dfrac{120\text{ V}\ \angle 0°}{340\ \Omega + j40\ \Omega} = \mathbf{0.351\text{ A}\ \angle -6.71°}$

e. $a\mathbf{V}_L = \dfrac{a^2 R_L \mathbf{V}_g}{(R_e + a^2 R_L) + jX_e} = \mathbf{I}_p a^2 R_L$

or $\mathbf{V}_L = a\mathbf{I}_p R_L \angle 0° = (4)(0.351\text{ A}\ \angle -6.71°)(20\ \Omega\ \angle 0°) = \mathbf{28.1\text{ V}\ \angle -6.71°}$

f. —

g. $V_L = \dfrac{N_s}{N_p} V_g = \dfrac{1}{4}(120\text{ V}) = \mathbf{30\text{ V}}$

16. a. $a = N_p/N_s = 4\text{ t}/1\text{ t} = 4,\ R_e = R_p + a^2 R_s = 4\ \Omega + (4)^2\ 1\ \Omega = 20\ \Omega$

$X_e = X_p + a^2 X_s = 8\ \Omega + (4)^2\ 2\ \Omega = 40\ \Omega$

$\mathbf{Z}_p = R_e + jX_e - ja^2 X_C = 20\ \Omega + j40\ \Omega - j(4)^2\ 20\ \Omega$

$= 20\ \Omega - j280\ \Omega = \mathbf{280.71\ \Omega\ \angle -85.91°}$

b. $\mathbf{I}_p = \dfrac{\mathbf{V}_g}{\mathbf{Z}_p} = \dfrac{120\text{ V}\ \angle 0°}{280.71\ \Omega\ \angle -85.91°} = \mathbf{0.427\text{ A}\ \angle 85.91°}$

c. $\mathbf{V}_{R_e} = (I_p \angle \theta)(R_e \angle 0°) = (0.427\text{ A}\ \angle 85.91°)(20\ \Omega\ \angle 0°) = \mathbf{8.54\text{ V}\ \angle 85.91°}$

$\mathbf{V}_{X_e} = (I_p \angle \theta)(X_e \angle 90°) = (0.427\text{ A}\ \angle 85.91°)(40\ \Omega\ \angle 90°) = \mathbf{17.08\text{ V}\ \angle 175.91°}$

$\mathbf{V}_{X_C} = (I_p \angle \theta)(a^2 X_C \angle -90°) = (0.427\text{ A}\ \angle 85.91°)(320\ \Omega\ \angle -90°) = \mathbf{136.64\text{ V}\ \angle -4.09°}$

18. Coil 1: $L_1 - M_{12}$

Coil 2: $L_2 - M_{12}$

$L_T = L_1 + L_2 - 2M_{12} = 4\text{ H} + 7\text{ H} - 2(1\text{ H}) = \mathbf{9\text{ H}}$

20. $M_{23} = k\sqrt{L_2 L_3} = 1\sqrt{(1\text{ H})(4\text{ H})} = 2\text{ H}$

Coil 1: $L_1 + M_{12} - M_{13} = 2\text{ H} + 0.2\text{ H} - 0.1\text{ H} = 2.1\text{ H}$

Coil 2: $L_2 + M_{12} - M_{23} = 1\text{ H} + 0.2\text{ H} - 2\text{ H} = -0.8\text{ H}$

Coil 3: $L_3 - M_{23} - M_{13} = 4\text{ H} - 2\text{ H} - 0.1\text{ H} = 1.9\text{ H}$

$L_T = 2.1\text{ H} - 0.8\text{ H} + 1.9\text{ H} = \mathbf{3.2\text{ H}}$

22. $\mathbf{Z}_i = \mathbf{Z}_p + \dfrac{(\omega M)^2}{\mathbf{Z}_s + \mathbf{Z}_L} = R_p + jX_{L_p} + \dfrac{(\omega M)^2}{R_s + jX_{L_s} + R_L}$

$R_p = 2\ \Omega,\ X_{L_p} = \omega L_p = (10^3\ \text{rad/s})(8\ \text{H}) = 8\ \text{k}\Omega$

$R_s = 1\ \Omega,\ X_{L_s} = \omega L_s = (10^3\ \text{rad/s})(2\ \text{H}) = 2\ \text{k}\Omega$

$M = k\sqrt{L_pL_s} = 0.05\sqrt{(8\ \text{H})(2\ \text{H})} = 0.2\ \text{H}$

$\mathbf{Z}_i = 2\ \Omega + j8\ \text{k}\Omega + \dfrac{(10^3\ \text{rad/s} \cdot 0.2\ \text{H})^2}{1\ \Omega + j2\ \text{k}\Omega + 20\ \Omega}$

$= 2\ \Omega + j8\ \text{k}\Omega + \dfrac{4 \times 10^4\ \Omega}{21 + j2 \times 10^3}$

$= 2\ \Omega + j8\ \text{k}\Omega + 0.21\ \Omega - j19.99\ \Omega = 2.21\ \Omega + j7980\ \Omega$

$\mathbf{Z}_i = \mathbf{7980\ \Omega\ \angle 89.98°}$

24. $I_s = I_1 = \mathbf{2\ A},\ E_p = V_L = \mathbf{40\ V}$

$V_gI_1 = V_LI_L \Rightarrow I_L = V_g/V_L \cdot I_1 = \dfrac{200\ \text{V}}{40\ \text{V}}(2\ \text{A}) = \mathbf{10\ A}$

$I_p + I_1 = I_L \Rightarrow I_p = I_L - I_1 = 10\ \text{A} - 2\text{A} = \mathbf{8\ A}$

26. a. $\mathbf{E}_2 = \dfrac{N_2}{N_1}\mathbf{E}_1 = \dfrac{15\ \text{t}}{90\ \text{t}}(60\ \text{V}\ \angle 0°) = \mathbf{10\ V\ \angle 0°}$

$\mathbf{E}_3 = \dfrac{N_3}{N_1}\mathbf{E}_1 = \dfrac{45\ \text{t}}{90\ \text{t}}(60\ \text{V}\ \angle 0°) = \mathbf{30\ V\ \angle 0°}$

$\mathbf{I}_2 = \dfrac{\mathbf{E}_2}{\mathbf{Z}_2} = \dfrac{10\ \text{V}\ \angle 0°}{8\ \Omega\ \angle 0°} = \mathbf{1.25\ A\ \angle 0°}$

$\mathbf{I}_3 = \dfrac{\mathbf{E}_3}{\mathbf{Z}_3} = \dfrac{30\ \text{V}\ \angle 0°}{5\ \Omega\ \angle 0°} = \mathbf{6\ A\ \angle 0°}$

b. $\dfrac{1}{R_1} = \dfrac{1}{(N_1/N_2)^2R_2} + \dfrac{1}{(N_1/N_3)^2R_3}$

$= \dfrac{1}{(90\ \text{t}/15\ \text{t})^2\ 8\ \Omega} + \dfrac{1}{(90\ \text{t}/45\ \text{t})^2\ 5\ \Omega}$

$\dfrac{1}{R_1} = \dfrac{1}{288\ \Omega} + \dfrac{1}{20\ \Omega} = 0.05347\ \text{S}$

$R_1 = \mathbf{18.70\ \Omega}$

28. $\mathbf{Z}_M = \mathbf{Z}_{M_{12}} = \omega M_{12}\ \angle 90°$

$\mathbf{E} - \mathbf{I}_1\mathbf{Z}_1 - \mathbf{I}_1\mathbf{Z}_{L_1} - \mathbf{I}_1(-\mathbf{Z}_m) - \mathbf{I}_2(+\mathbf{Z}_m) - \mathbf{I}_1\mathbf{Z}_{L_2} + \mathbf{I}_2\mathbf{Z}_{L_2} - \mathbf{I}_1(-\mathbf{Z}_m) = 0$

$\mathbf{E} - \mathbf{I}_1(\mathbf{Z}_1 + \mathbf{Z}_{L_1} - \mathbf{Z}_m + \mathbf{Z}_{L_2} - \mathbf{Z}_m) - \mathbf{I}_2(\mathbf{Z}_m - \mathbf{Z}_{L_2}) = 0$

or $\mathbf{I}_1(\mathbf{Z}_1 + \mathbf{Z}_{L_1} + \mathbf{Z}_{L_2} - 2\,\mathbf{Z}_m) + \mathbf{I}_2(\mathbf{Z}_m - \mathbf{Z}_{L_2}) = \mathbf{E}$

$-\mathbf{I}_2\mathbf{Z}_2 - \mathbf{Z}_{L_2}(\mathbf{I}_2 - \mathbf{I}_1) - \mathbf{I}_1(+\mathbf{Z}_m) = 0$

or $\mathbf{I}_1(\mathbf{Z}_m - \mathbf{Z}_{L_2}) + \mathbf{I}_2(\mathbf{Z}_2 + \mathbf{Z}_{L_2}) = 0$